Foundations of Hybrid and Embedded Software and Systems: Project Overview

Edited and presented by
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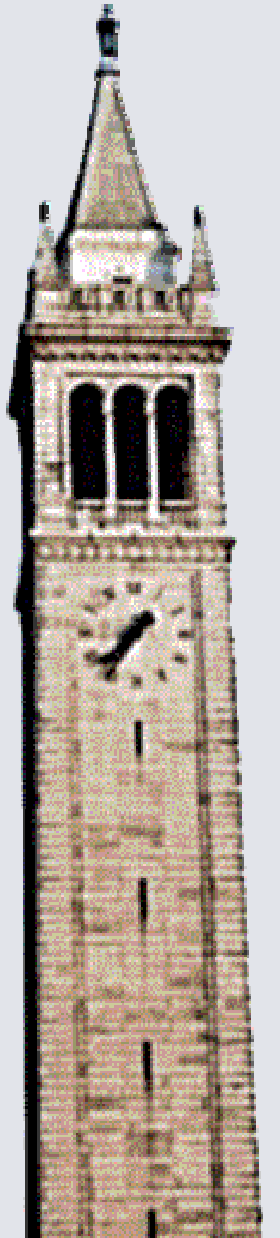
UC Berkeley



Chess Review
November 21, 2005
Berkeley, CA

NSF-ITR Investigators

Ruzena Bajcsy, Ras Bodik, Bela Bollobas, Gautam Biswas, Tom Henzinger, Kenneth Frampton, Gabor Karsai, Kurt Keutzer, John Koo, Edward Lee, George Necula, Alberto Sangiovanni Vincentelli, Shankar Sastry, Janos Sztipanovits, Claire Tomlin, Pravin Varaiya.

ITR-Center Mission

- The goal of the ITR is to provide an environment for graduate research on the design issues necessary for supporting next-generation embedded software systems.
  - The research focus is on developing model-based and tool-supported design methodologies for real-time fault-tolerant software on heterogeneous distributed platforms.
- The Center maintains a close interaction between academic research and industrial experience.
  - A main objective is to facilitate the creation and transfer of modern, "new economy" software technology methods and tools to "old economy" market sectors in which embedded software plays an increasingly central role, such as aerospace, automotive, and consumer electronics.

Mission of Chess

To provide an environment for graduate research on the design issues necessary for supporting next-generation embedded software systems.

- Model-based design
- Tool-supported methodologies

For

- Real-time
- Fault-tolerant
- Robust
- Secure
- Heterogeneous
- Distributed Software

We are on the line to create a "new systems science" that is at once computational and physical.

Hybrid and Embedded Software:
Problem for Whom and What have we done

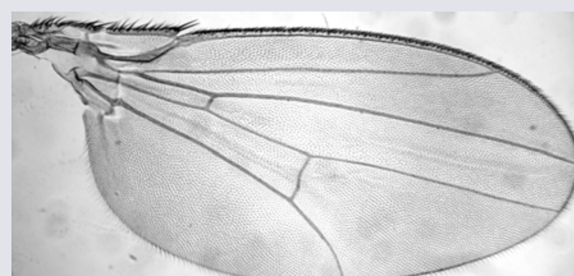
- DoD (from avionics to micro-robots)
  - Essential source of functionality/superiority
  - UAV flight control, F-22/F-35 avionics, UAR
- Automotive (drive-by-wire(less)?)
  - Key competitive element:
  - Studies for Ford, GM, Toyota, Siemens
- Ubiquitous Computing Devices (from mobile phones to TVs to sensor webs)
  - Networked Embedded Systems
  - Several generations of Sensor Webs/Motes
- Plant Automation Systems
  - SCADA/DCS in Critical Infrastructure Protection
  - Closing the loop around sensor webs

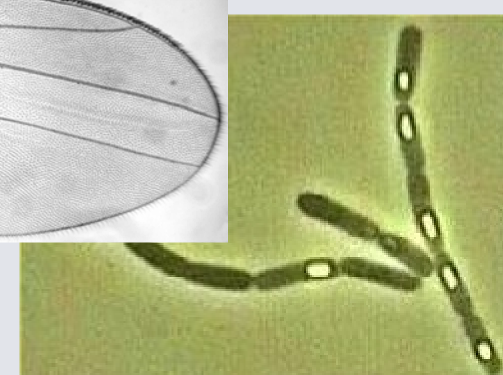
Some Applications Addressed

Automotive

Avionics: UAVs

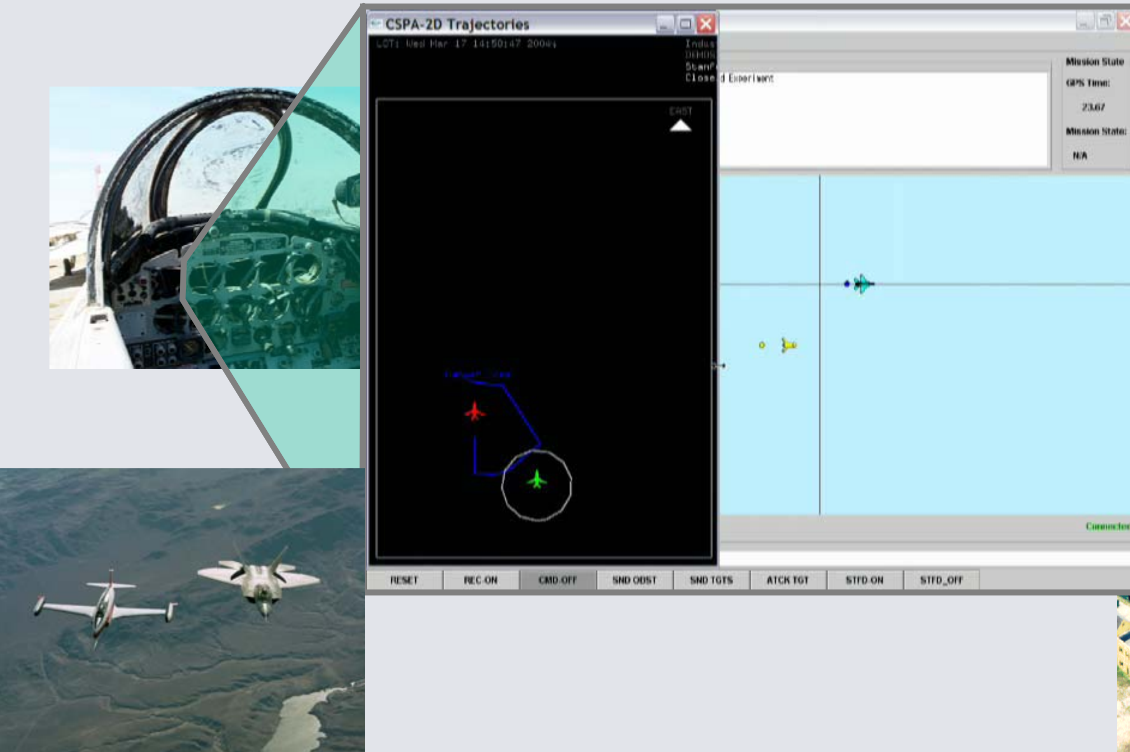
Systems Biology





Networked
Embedded Systems

More Applications



Shooter Localization using Vanderbilt Algorithms

Conflict Detection and Resolution for Manned and Unmanned Aircraft

Project Approach

- Model-Based Design (the view from above)
  - principled frameworks for design
  - specification, modeling, and design
  - manipulable (mathematical) models
  - enabling analysis and verification
  - enabling effective synthesis of implementations
- Platform-Based Design (the view from below)
  - exposing key resource limitations
  - hiding inessential implementation details
- Tools
  - concrete realizations of design methods

Key Properties of Hybrid & Embedded Software Systems

- Computational systems
  - but not first-and-foremost a computer
- Integral with physical processes
  - sensors, actuators
- Reactive
  - at the speed of the environment
- Heterogeneous
  - hardware/software, mixed architectures
- Networked
  - adaptive software, shared data, resource discovery
  - Ubiquitous and pervasive computing devices

Foundational Research

- The science of computation has systematically abstracted away the physical world. The science of physical systems has systematically ignored computational limitations. Embedded software systems, however, engage the physical world in a computational manner.
- We believe that it is time to construct an Integrated Systems Science (ISS) that is simultaneously computational and physical. Time, concurrency, robustness, continuums, and resource management must be remarried to computation.
- Mathematical foundations: Hybrid Systems Theory: Integrated Systems Science.

… and Embedded Software Research

- Models and Tools:
  - Model-based design (platforms, interfaces, meta-models, virtual machines, abstract syntax and semantics, etc.)
  - Tool-supported design (simulation, verification, code generation, inter-operability, etc.)
- Applications:
  - Flight control systems
  - Automotive electronics
  - National experimental embedded software platform
- From resource-driven to requirements-driven embedded software development.

Some Current Research Focus Areas

- Software architectures for actor-oriented design
- Interface theories for component-based design
- Virtual machines for embedded software
- Semantic models for time and concurrency
- Design transformation technology (code generation)
- Visual syntaxes for design
- Approximate Solutions to H-J equations and controller synthesis
- Autonomous rotorcraft
- Automotive systems design
- Networked Embedded Systems
- Systems Biology

Tool Development Efforts

- GME
- GReAT
- DESERT
- Fresco
- Giotto/Massaccio
- Ptolemy
- HyVisual
- Metropolis
- Hyper
- MESCAL

NSF ITR Organization

- PI: Shankar Sastry
- coPIs: Tom Henzinger, Edward Lee, Alberto Sangiovanni-Vincentelli, Janos Sztipanovits
- Participating Institutions: UCB, Vanderbilt, Memphis
- Five Thrusts:
  - Hybrid Systems Theory (Tomlin/Henzinger)
  - Model-Based Design (Sztipanovits)
  - Advanced Tool Architectures (Lee)
  - Applications: automotive (ASV), aerospace (Tomlin/Sastry), biology (Tomlin)
  - Education and Outreach (Karsai, Lee, Varaiya)
- Five year project: kick-off meeting November 14th , 2002. Reviews May 8th, 2003, Dec 3rd, 2003, May 10th, 2004, Nov 18th 2004, May 12th, 2005, etc.
  - Weekly seminar series
  - Ptolemy workshop May 9th, 2003, April 27th 2004,
  - NEST + CHESS Workshop May 9th, 2003
  - BEARS Open House, February 27th 2004, February 25th, 2005

Thrust 1 Hybrid Systems

- Deep Compositionality
  - Assume Guarantee Reasoning for Hybrid Systems
  - Practical Hybrid System Modeling Language
  - Interface Theory for hybrid components (Chakrabarty)
- Robust Hybrid Systems
  - Bundle Properties for hybrid systems
  - Topologies for hybrid systems (Ames)
  - Stochastic hybrid systems (Abate, Amin)
- Computational hybrid systems
  - Approximation techniques for H-J equations (Mitchell, Bayen)
  - Synthesis of safe and live controllers for hybrid systems
- Phase Transitions and Network Embedded Systems

Thrust II: Model Based Design

- Composition of Domain Specific Modeling Languages
  - Meta Modeling
  - Components to manipulate meta-models
  - Integration of meta-modeling with hybrid systems
- Model Synthesis Using Design Patterns
  - Pattern Based Modal Synthesis
  - Models of Computation
  - Design Constraints and Patterns for MMOC
- Model Transformation
  - Meta Generators
  - Semantic Anchoring
  - Construction of Embeddable Generators

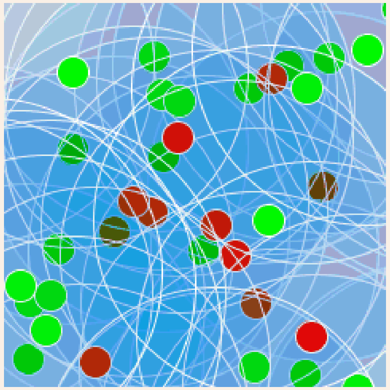
Thrust III: Advanced Tool Architectures

- Syntax and Synthesis
  - Semantic Composition
  - Visual Concrete Syntaxes
  - Modal Models
- Interface Theories
- Virtual Machine Architectures
- Components for Embedded Systems

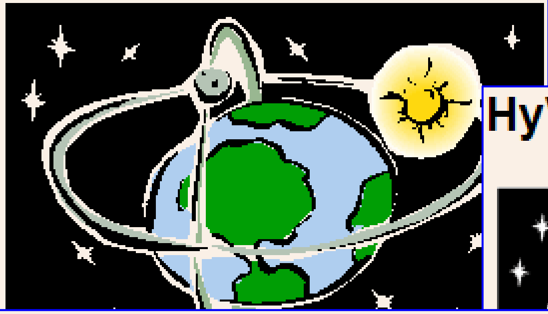
Software Releases

VisualSense

Visual editor and simulator for wireless sensor network systems

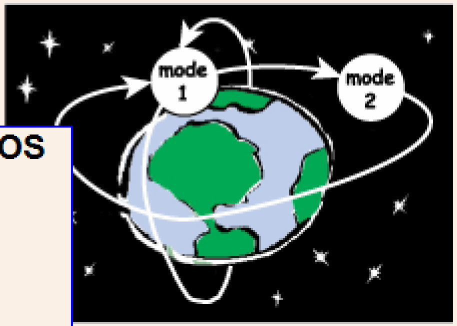


Ptolemy II



Metropolis: Design Environment for Heterogeneous Systems

HyVisual - Hybrid System Visual Modeler



Viptos - Visual interface between Ptolemy and TinyOS

The Hyper toolbox (in development)

- Inspired by hybrid systems domain
- Consider Interchange Format Philosophy:
  - For all models which *could be* built in Tool_1 or Tool_2 (i.e., as defined by A_1) there must exist a translator to/from an Interchange Format
- Alternative philosophy:
  - For a model, *m*, built in Tool_1 or Tool_2, this model may be translated to the other tool *if* the semantics used by *m* are an intersecting subset of the semantics $S_1 \cap S_2$.

$\text{Tool}_1 = \langle C_1, A_1, S_1, M_{s1}, M_{c1} \rangle$

C = Concrete Syntax, A = Abstract Syntax, S = Semantics
M_s = Semantic Mapping, M_c = Concrete Syntax Mapping

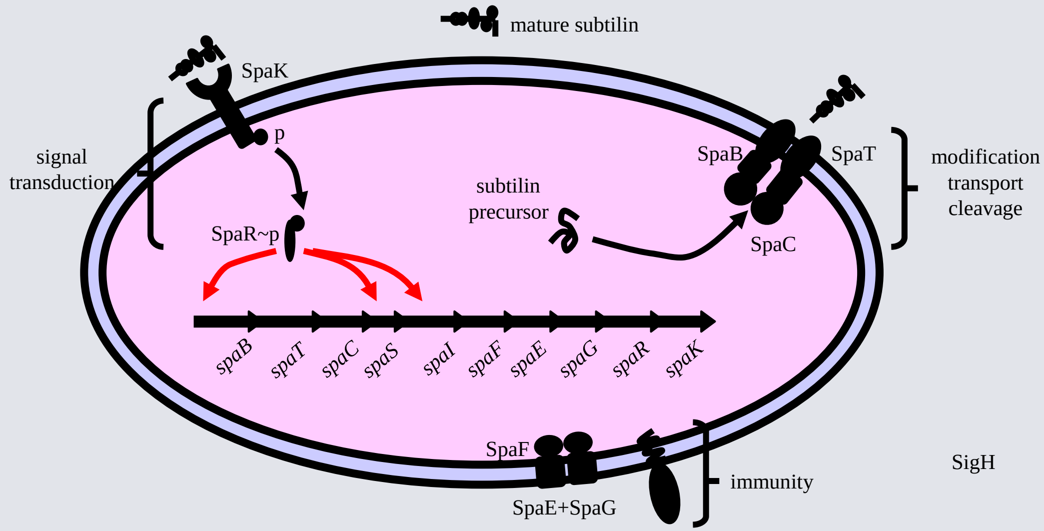
The Hyper toolbox (in development)

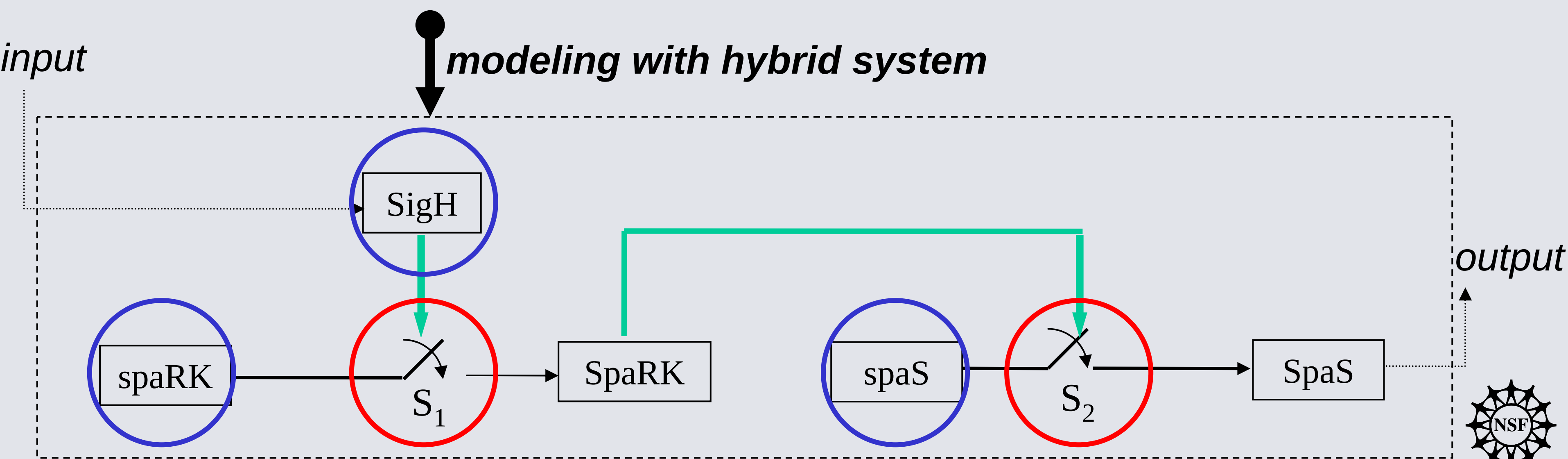
- Examine semantics used by a model to determine compatibility
- This provides several potential uses
  - Produce $\text{Tool}_{1\cap 2}$ after user request for models compatible across Tool_1, Tool_2
  - Check to see if model m_3, produced in $\text{Tool}_{1\cap 3}$ is compatible with Tool_2
  - Produce $\text{Tool}_{\text{simulate}\cap\text{verify}}$ when capability is more important than specific semantics
- Implementation strategy
  - Strong typing, metamodeling of type structures
  - Previous Chess work in operational semantics and Interchange Formats

Thrust IV: Applications

- Embedded Control Systems
  - Avionics: F-22, F-35, UAV flight control, Open Control Platform
  - Veitronics: Engine control, Braking control, architectures
- Embedded Systems for National/Homeland Security
  - Air Traffic Control; Smart Walls, Sector Control
  - UAVs: flight control, autonomous navigation, landing
- Networks of Distributed Sensors and Networked Embedded Systems
- Stochastic Hybrid Systems in Systems Biology
- Hybrid Models in Structural Engineering
  - Active Noise Control
  - Vibration damping of complex structures

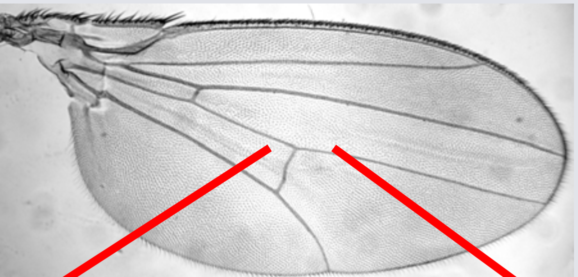
Antibiotic biosynthesis in *Bacillus subtilis*

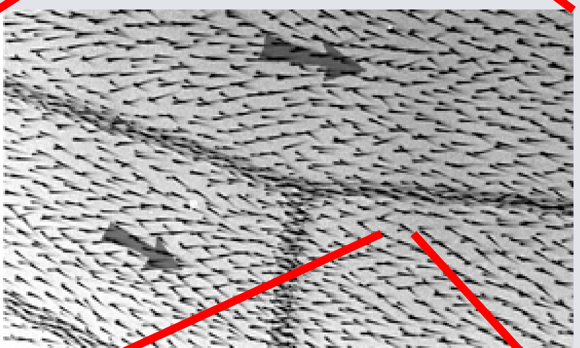




= *discrete states (with randomness)*   = *continuous states*

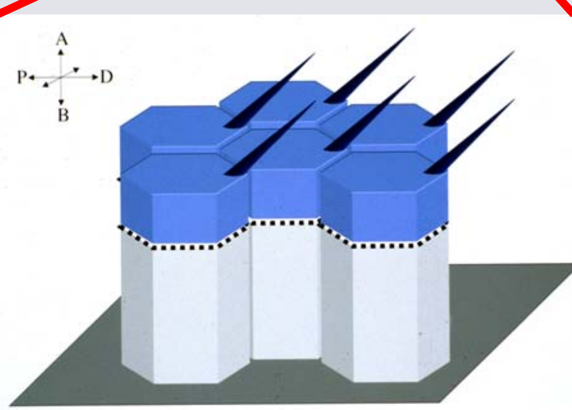
Planar cell polarity in *Drosophila*



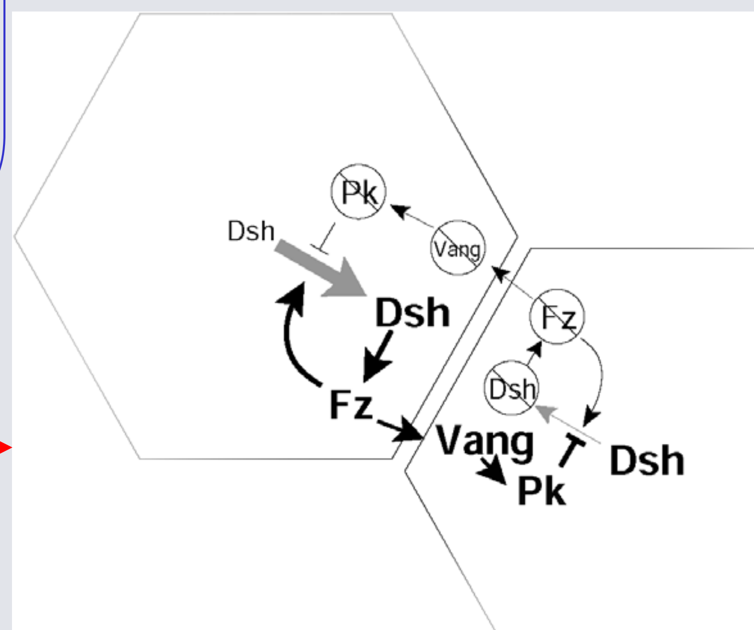


phenotype

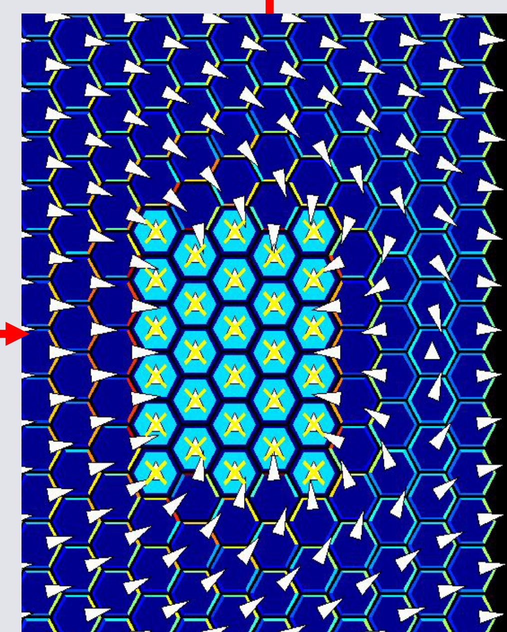
- •Simulations
- •Parameters estimation
- •Study of mutants



cell model



proteins feedback network



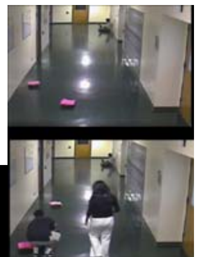
Thrust V: Education and Outreach

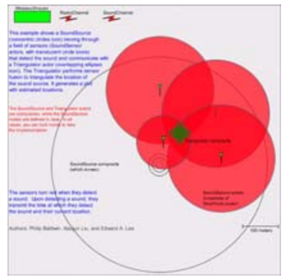
- Curriculum Development for MSS
  - Lower Division
  - Upper Division
  - Graduate Courses
- Undergrad Course Insertion and Transfer
  - New courses for partner institutions (workshops held March 1st 2003, Summer 2004), ABET requirements
  - Introduction of new undergrad control course at upper division level by embedded control course coordinated with San Jose State
  - CHESS-SUPERB/ Summer Program in Embedded Software Research SIPHER program (6 + 4 students in Summer 03, 3 + 5 in Summer 04, 6+4 students in Summer 05)
- Graduate Courses
  - EECS 249 Design of Embedded Systems: Models, Validation, and Synthesis
  - EECS 290N Concurrent Models of Computation for Embedded Software
  - Vanderbilt EECE 395 / EECS 291E/ME 290S Hybrid Systems

SUPERB: Projects Overview

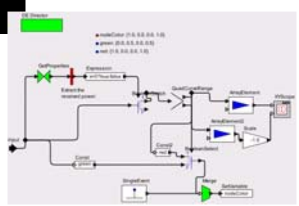
Camera Networks

Lana Carnel





Visual Segmentation Code

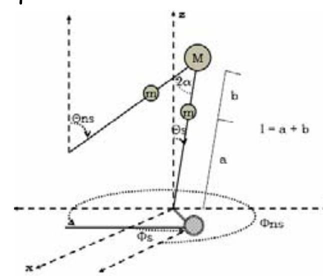


Camera and Network Modeling

Murphy Gant

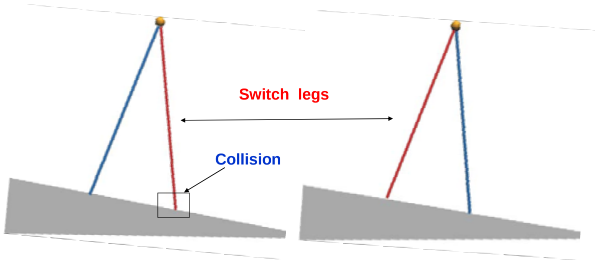
Hybrid Systems Theory and Modeling

Derivation of Equations of Motion



Bobby Gregg

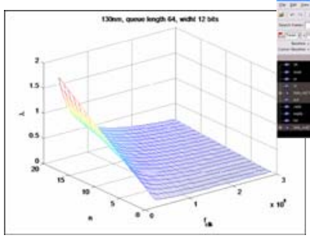
Simon Ng



Modeling and Simulation with HyVisual

Modeling/Analysis On-Chip Networks

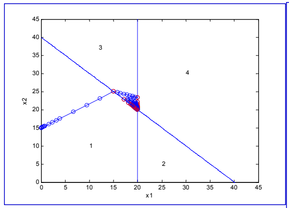
Reinaldo Romero

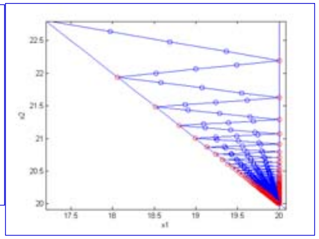


Tradeoff Analysis in Design

Zeno in Communications Networks

Shams Karimkhan





SIPHER Student Projects

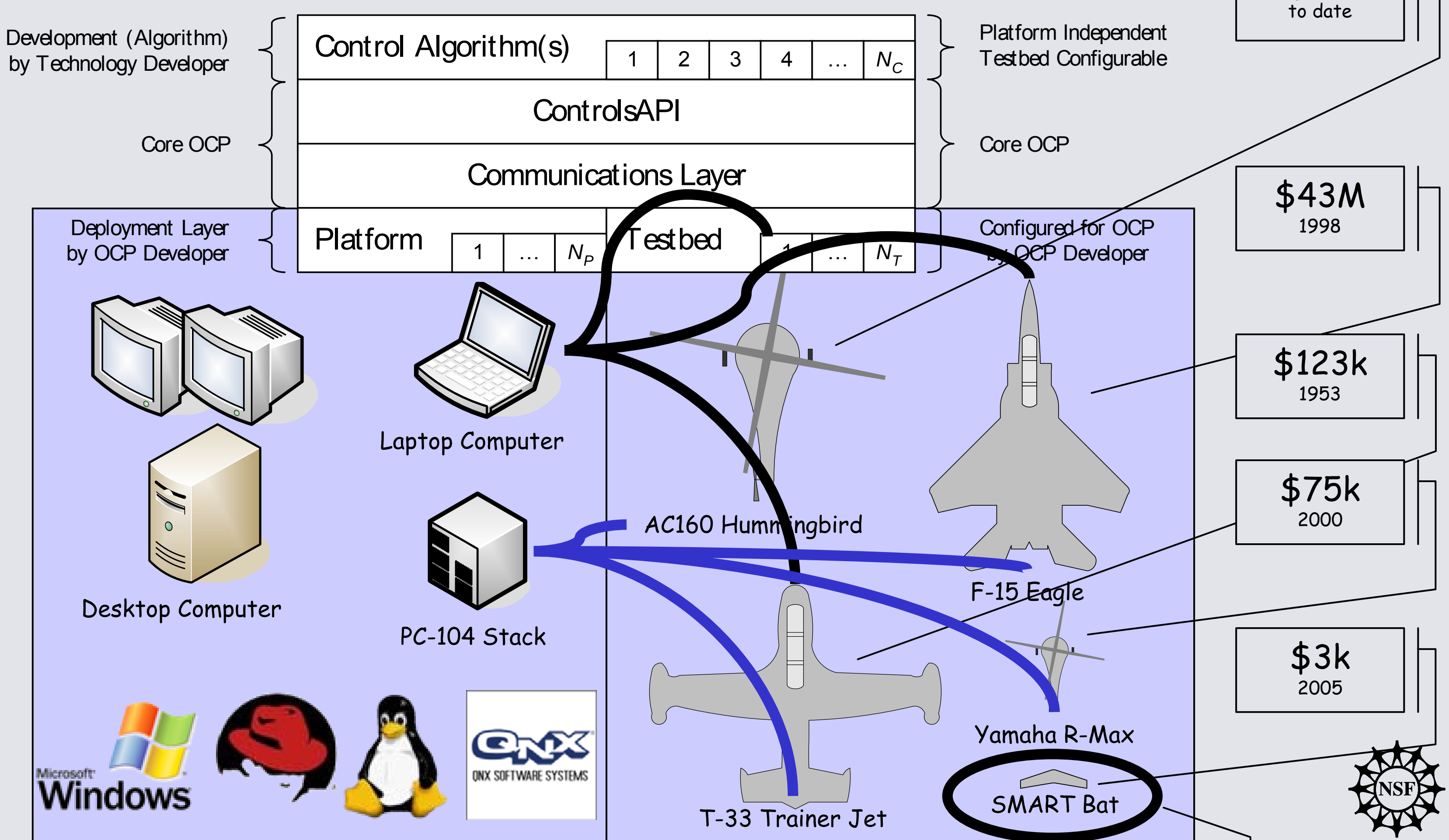
- Process Control using Model-based Tools
  - Karlston Martin
  - Shantell Hinton
- Embedded Controllers for Vibration Control
  - Alicia Vaden
- Sensor Networks – Camera Control
  - Chanel Mitchell
  - Omar Abdul-Ali
- Autonomous Robot Control
  - Lauren Mitchell
  - Sarah Francis
- Embedded Software Tools
  - Ryan Thibodeaux

Outreach Continued

- Interaction with EU-IST programs
  - Columbus (with Cambridge, l'Aquila, Rome, Patras, INRIA)
  - Hybridge, Hycon (with Cambridge, Patras, NLR, Eurocontrol, Brescia, KTH)
  - ARTISTE, ARTIST-2: Educational Initiatives (Grenoble, INRIA, ETH-Zurich)
  - RUNES EU-IST program in network embedded systems (Ericsson, KTH, Aachen, Brescia, Pisa, Patras, …)
  - EU-US Embedded Systems meeting, Paris, July 2005 organized by Sztipanovits
- Foundation of non-profit ESCHER
  - Interaction with F-22/JSF design review teams
  - Secure Networked Embedded Systems: TinyOS, Tiny DB, etc.
  - Bio-SPICE repository

The Embedded Open Control Platform (EOCP)

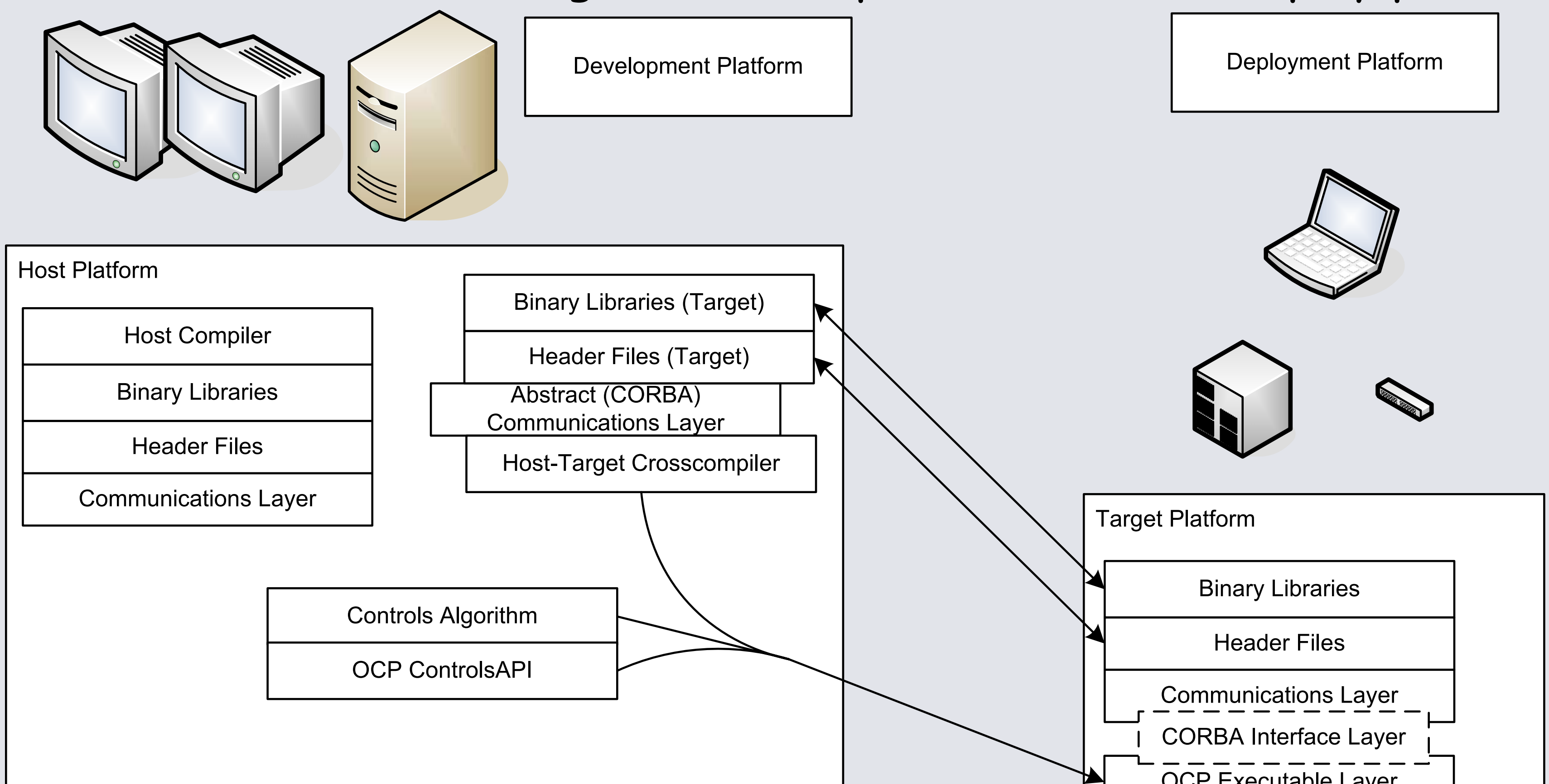
OCP provides an insulation layer between software-based control algorithms and the testbed/platform/OS on which they run.



No existing platform of appropriate form-factor/weight

Development, Deployment, and Demystification

Objective: Separate development and deployment platforms, provide out-of-the-box self-configuration scripts for new dev/deploy platforms



Benefit: Allow OCP developers to not necessarily be Unix Developers

Outreach Continued

- Three NITRD-HCSS studies
  - High Confidence Medical Devices and Systems: Philadelphia, June 2005. Sastry, Sztipanovits organizing committee members, follow up meeting at Vanderbilt: Dec. 2005
  - Aviation Safety and Certification: Planning Meeting Seattle Nov 9, 10th 2005. Tomlin main study leader main meeting
  - High Confidence SCADA systems: Planning meeting, Washington, DC March 21-23, 2006
- NSF-EU workshop to be held in Helsinki, June 2006

Network Embedded Systems: A Progress Report

Edited and presented by
Shankar Sastry
UC Berkeley

Chess Review
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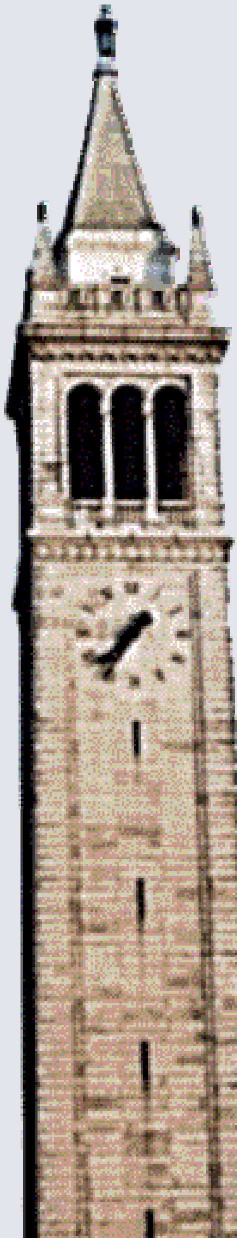
Berkeley, CA



Bell's Law –
new computer class per 10 years

log (people per computer)

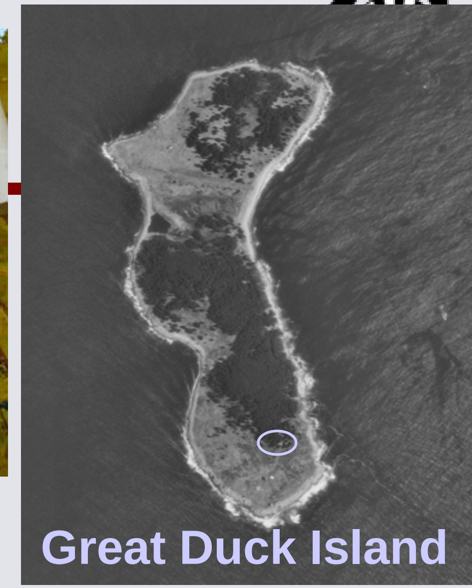
Number Crunching
Data Storage

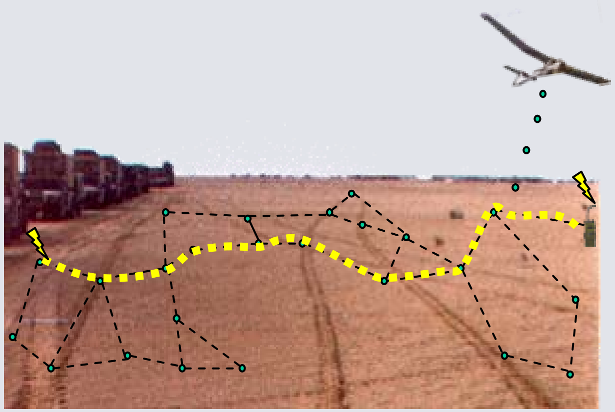
productivity
interactive

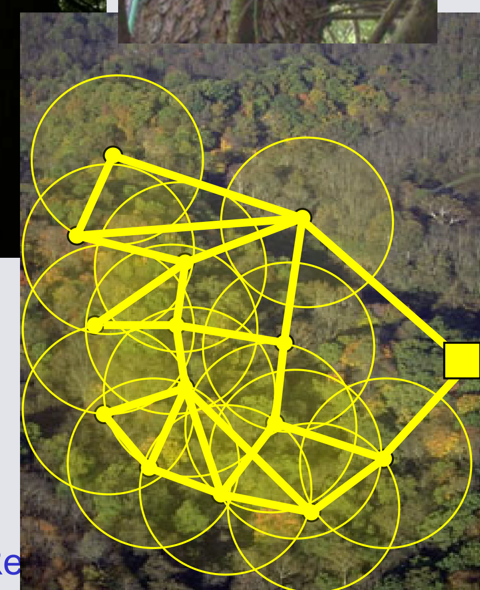
streaming information to/from physical world

- Enabled by technological opportunities
- Smaller, more numerous and more intimately connected
- Ushers in a new kind of application
- Ultimately used in many ways not previously imagined

Instrumenting the world





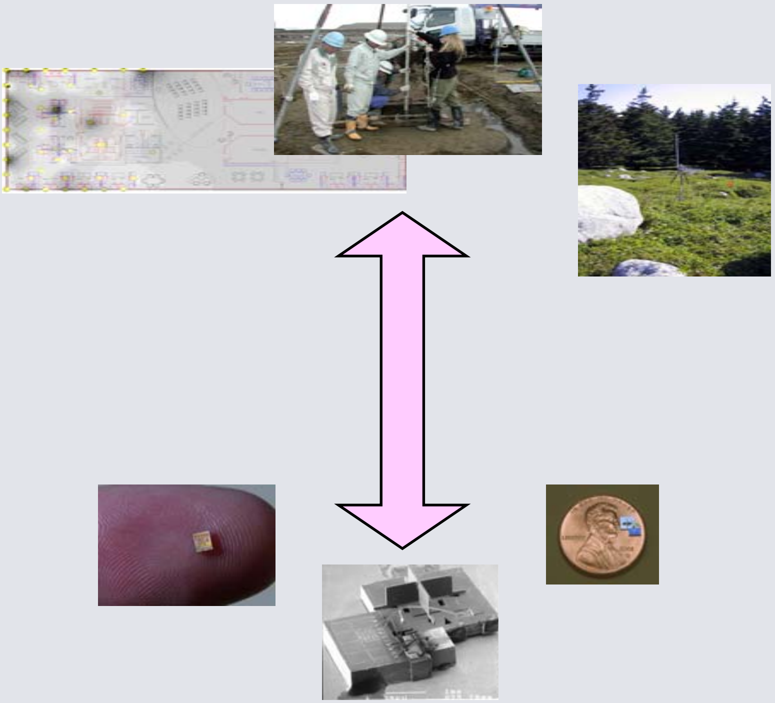


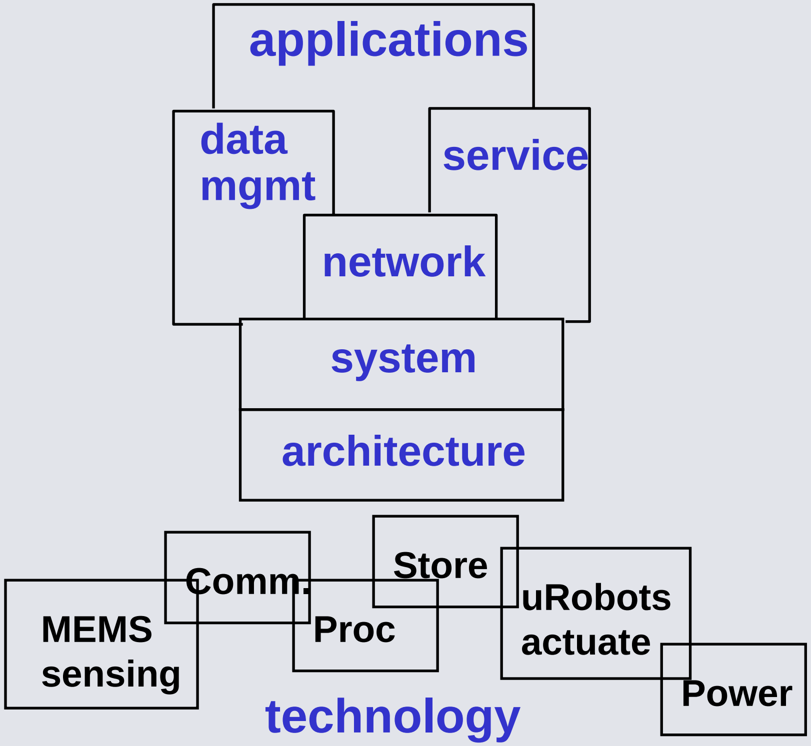
Elder Care

Factories

The Sensor Network Challenge

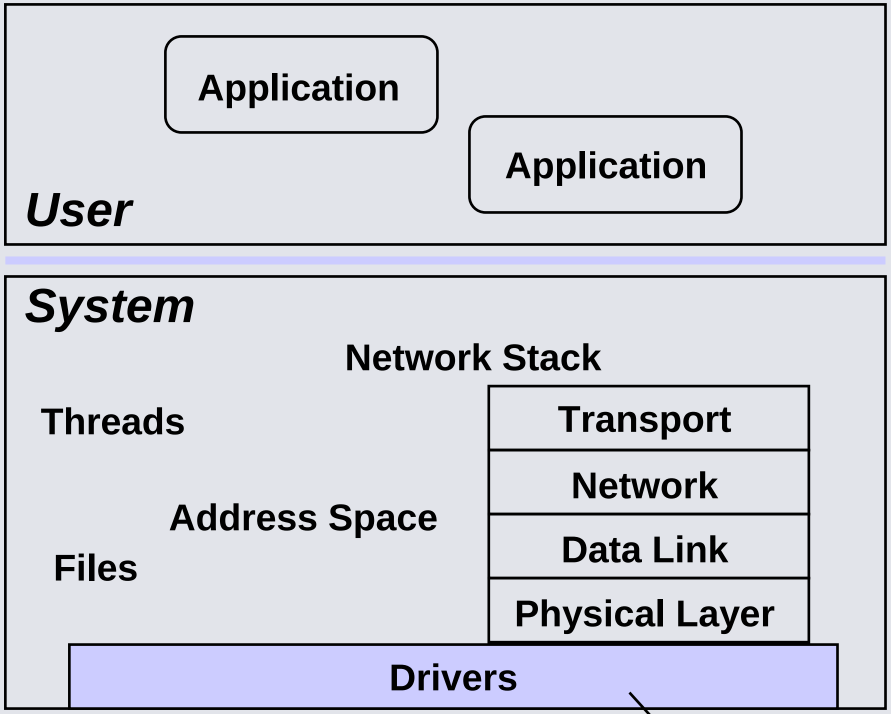
Monitoring & Managing Spaces and Things



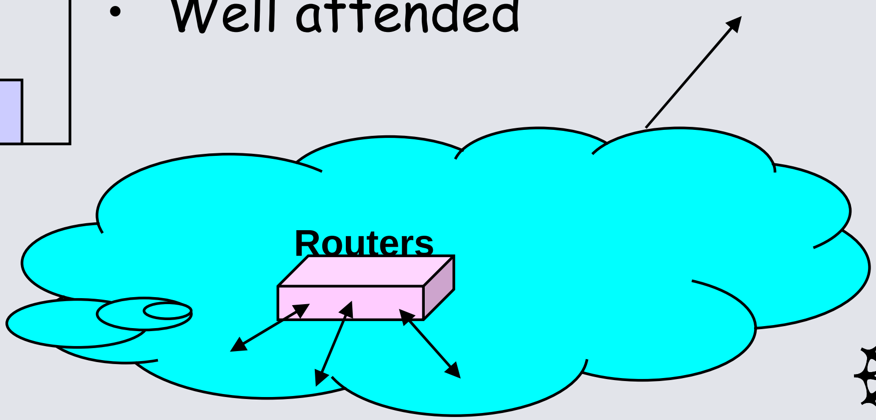


Miniature, low-power connections to the physical world

Traditional Systems



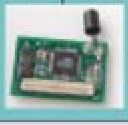
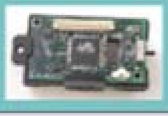
- Well established layers of abstractions
- Strict boundaries
- Ample resources
- Independent Applications at endpoints communicate pt-pt through routers
- Well attended



by comparison ...

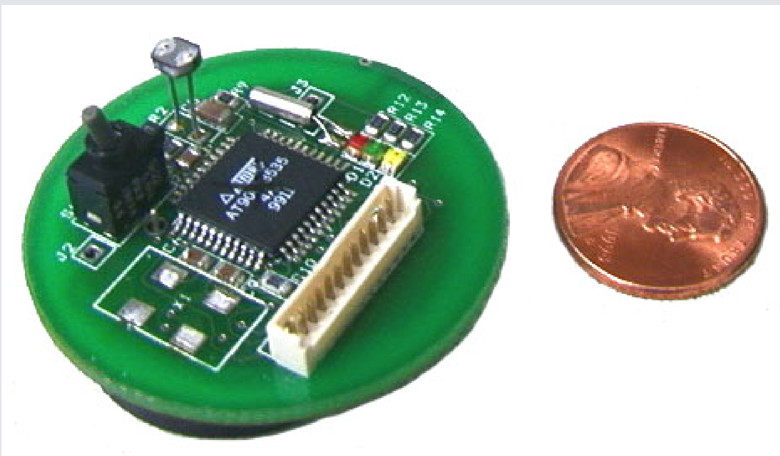
- Highly Constrained resources
  - processing, storage, bandwidth, power
- Applications spread over many small nodes
  - self-organizing Collectives
  - highly integrated with changing environment and network
  - communication is fundamental
- Concurrency intensive in bursts
  - streams of sensor data and network traffic
- Robust
  - inaccessible, critical operation
- Unclear where the boundaries belong
  - even HW/SW will move

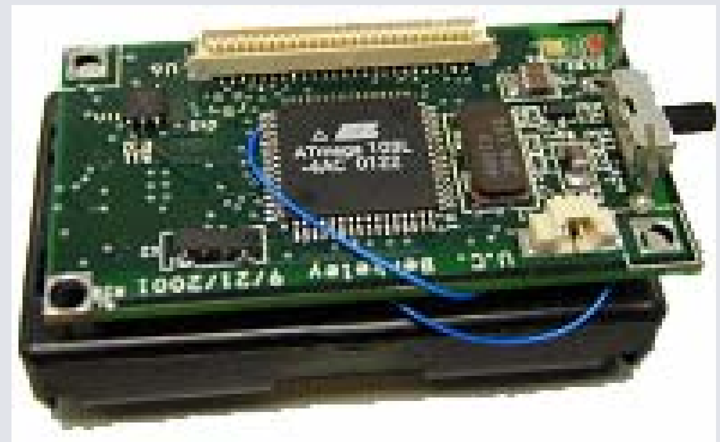
Mote Evolution

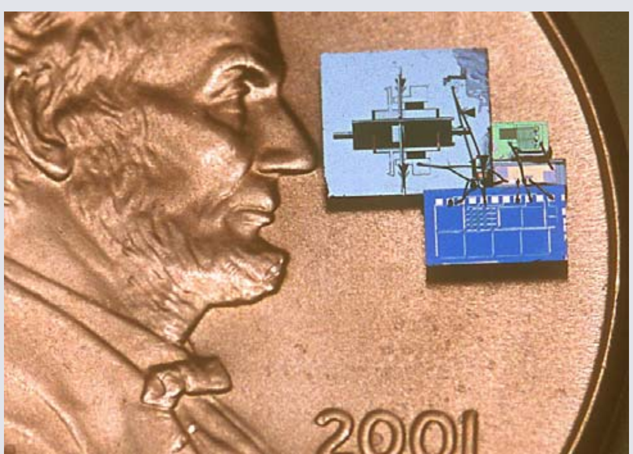
Mote Type Year	*WeC* 1998	*René* 1999	*René 2* 2000	*Dot* 2000	*Mica* 2001	*Mica2Dot* 2002	*Mica 2* 2002	*Telos* 2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			48
RAM (KB)	0.5		1		4			10
Active Power (mW)	15		15		15		60	0.5
Sleep Power (μW)	45		45		75		75	2
Wakeup Time (μs)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	38.5
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

Evolution of Motes Continued

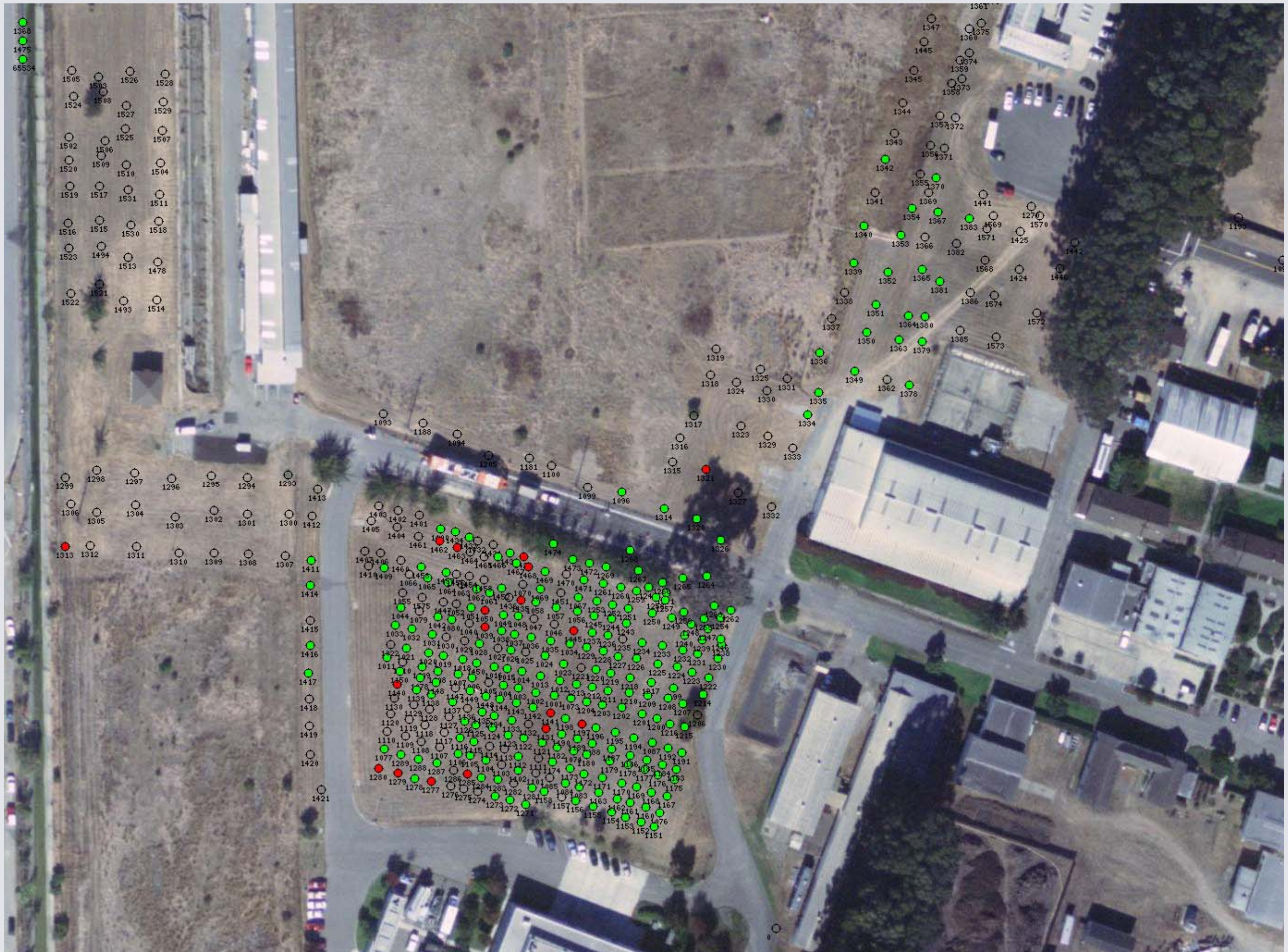
Dot motes, MICA motes, smart dust, Telos motes







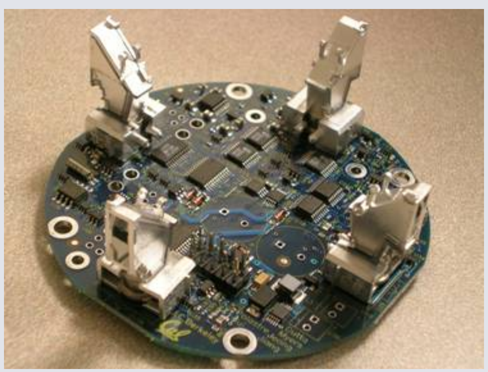
NEST Final Experiment Deployment August 2005



NEST Final Experiment: Sensor Node

Telos B mote

- 8MHz TI MSP430 microcontroller
- RAM: 10kB; Flash: 48kB
- Chipcon CC2420 Radio: 250kbps, 2.4GHz, IEEE 802.15.4 standard compliant
- Radio range of up to 125 meters



Trio Sensor Board

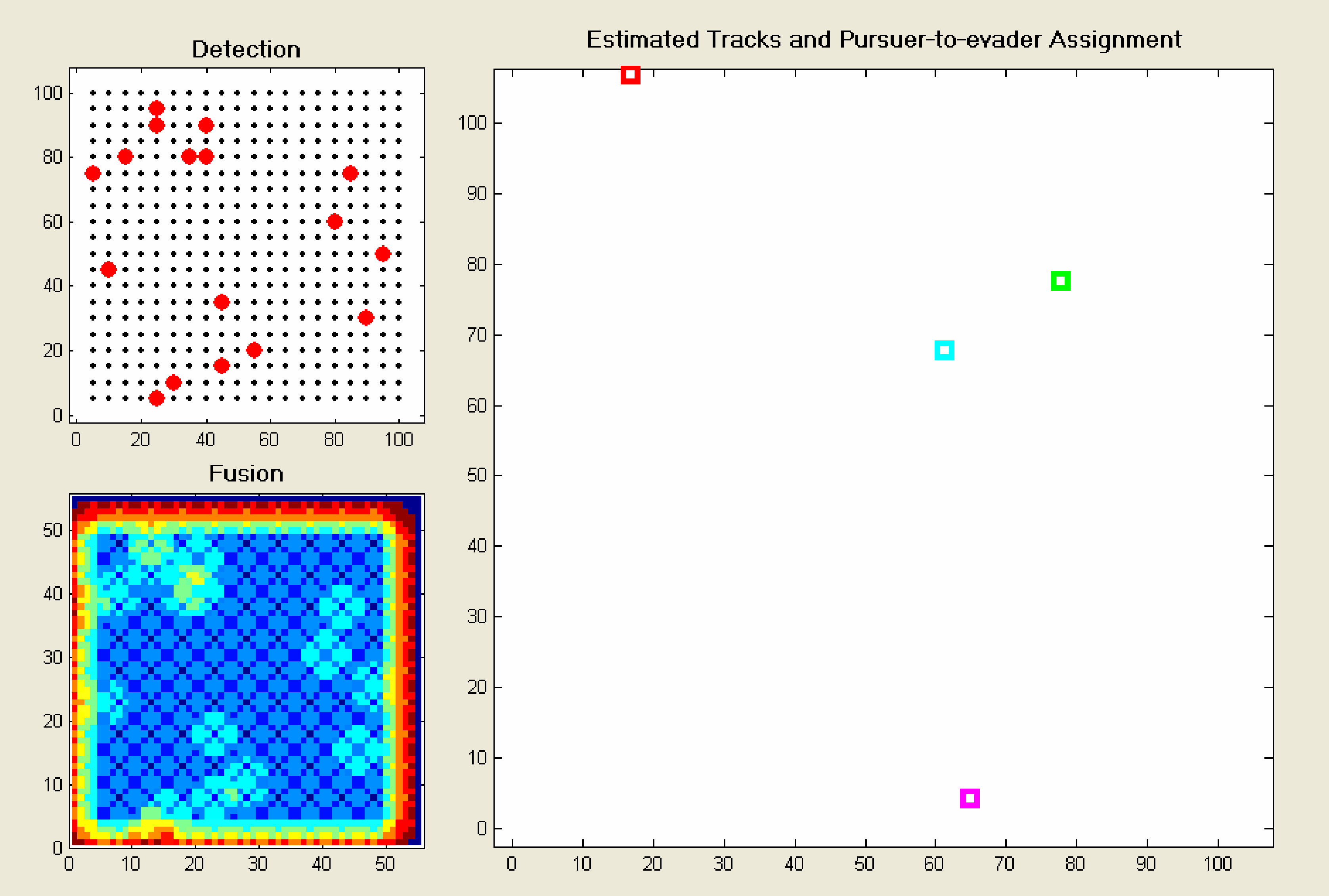
- Features a microphone, a piezoelectric buzzer, x-y axis magnetometers, and four passive infrared (PIR) motion sensors
- Solar-power charging circuitry

Trio Node

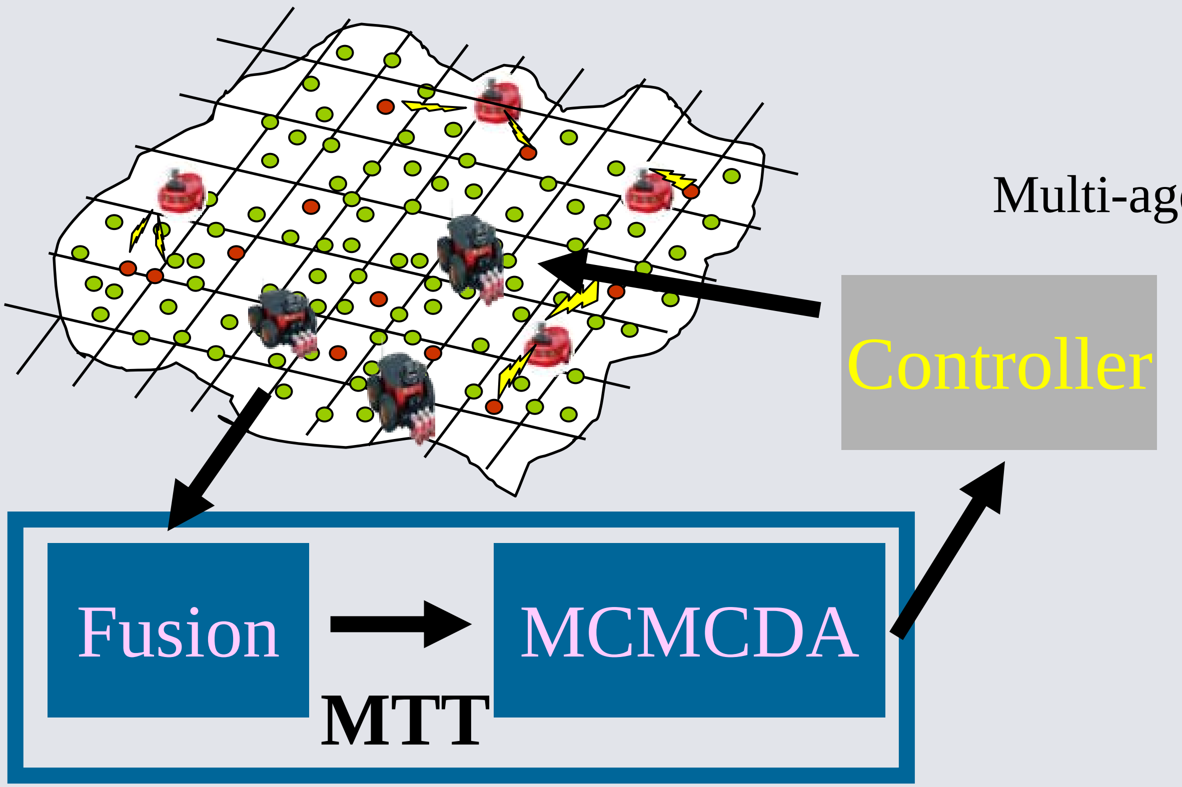
Multiple Target Tracking

- Goal
  - Track an **unknown** number of ***multiple targets*** using a sensor network of **binary** sensors **without classification** information
  - Coordinate ***multiple pursuers*** to chase and capture ***multiple evaders*** in **minimum time** using a sensor network
    - Done in simulation due to physical and time constraints

Simulation: Multiple-Target Tracking & Pursuit Evasion Games in Sensor Networks



Overall Architecture



Multi-agent coordination algorithm

- Minimize time to capture all evaders
- Robust Minimum Time Control (MTC)

NEST Final Experiment: System

- Software
  - TinyOS
  - Deluge
    - Network reprogramming
  - Drip and Drain (Routing Layer)
    - Drip: disseminate commands
    - Drain: collect data
  - DetectionEvent
    - Multi-moded event generator
  - Multi-sensor fusion and multiple-target tracking algorithms

SCADA of the Future

- Current SCADA
  - Closed systems, limited coordination, unprotected cyber-infrastructure
  - Local, limited adaptation (parametric), manual control
  - Static, centralized structure
- Future requirements
  - Decentralized, secure open systems (peer-to-peer, mutable hierarchies of operation)
  - Direct support for coordinated control, authority restriction
  - Trusted, automated reconfiguration
    - Isolate drop-outs, limit cascading failure, manage regions under attack
    - Enable re-entry upon recovery to normal operation
    - Coordinate degraded, recovery modes
  - Diagnosis, mitigation of combined physical, cyber attack
  - Advanced SCADA for productivity, market stability, manageability

Layers of Secure Network Embedded Systems

- Physical Layer
  - Attacks: jamming, tampering
  - Defenses: spread spectrum, priority messages, lower duty cycle, region mapping, mode change, tamper proofing, hiding.
- Link Layer
  - Attacks: collision, exhaustion, unfairness
  - Defenses: error correcting code, rate limitation, small frames

Layers of Secure Network Embedded Systems

- Network and Routing Layer
  - Attacks: neglect and greed, homing, misdirection, black holes
  - Defenses: redundancy, probing, encryption, egress filtering, authorization, monitoring, authorization, monitoring, redundancy
- Transport Layer
  - Attacks: flooding, desynchronization
  - Defenses: client puzzles, authentication
- Embedded System/Application Layer
  - Attacks: insider misuse, unprotected operations, resource overload attacks, distributed service disruption
  - Defenses: authority management (operator authentication, role-based control authorization), secure resource management, secure application distribution services